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Drilling Waste Slurries: Engineering their Properties for Waste Management Solutions

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Abstract

The legislation governing disposal of drilling waste during offshore operations is continually tightening the environmental discharge limits and in some cases this has led to total containment of waste. One of the consequences of this move in the industry is to find solutions for containing, transporting, transferring and disposing of large volumes of heterogeneous waste materials. One option is to slurry the drilling waste to enable direct pumping and transfer of the material.

During the slurrification process we need to minimise dilution to reduce slurry volumes whilst maintaining a slurry which can be pumped using the equipment available. We therefore require techniques to enable measurement of slurry viscosity during the slurry optimisation process. In this study two methods have been adopted, the coaxial cylinder viscometer and a pipe viscometer. The coaxial cylinder viscometer proved very useful in screening various surfactant chemistries to improve the viscosity of the slurry suspensions whilst retaining some slurry stability to settling. The pipe viscometer provided important information on the pumpability of the slurries and the effectiveness of various treatment regimes.

Introduction

The legislation governing disposal of drilling waste during offshore operations, in certain oilfields, has led to the total containment of waste. Where disposal is still allowed, the legislation is continually tightening the discharge limits. The consequence of this move in the industry is to find solutions for containing, transporting, transferring and disposing of large volumes of heterogeneous waste materials. The discussions covered in this paper will focus on offshore waste management, although the engineering solutions identified in this context could easily be applied to onshore applications where the need arises.

Currently there are various solutions for managing and disposing of off-shore drilling waste, including cuttings re-injection (CRI), 'skip and ship' transfer systems (including vacuum and auger feeds), bulk slurry transfer systems and pneumatic bulk transfer systems. Apart from CRI, all the others require land-based disposal of the waste, either with or without some form of remediation, depending on the local legislation and technology available. Where direct pumping of the waste occurs, there is invariably the need to slurry the rock cuttings in a carrier fluid. During the slurrying process it is very important to minimise the dilution of the waste by the carrier fluid, both from an environmental management point of view and from a cost point of view (i.e. where the logistical and disposal costs are based on volumes of material handled). It is a cornerstone of waste management policy to minimise waste at source [Ref 1]. However, we also require a slurry which can be pumped and transferred using the equipment and facilities available. The requirement is therefore to achieve a balance between engineering a stable, pumpable slurry whilst dilution is minimised.

The results reported and discussed in this paper concentrate on evaluation of oil mud cuttings slurried in two different carrier fluids; oil-based fluid (OBF) and seawater. Both carrier fluids (also termed dilution fluids) have applications, depending on the drivers for the cuttings remediation and disposal. For example, if thermal treatment of the cuttings is to be used, then oil based mud (OBM) can be the dilution fluid, as in some applications in the UK North Sea. However, there are also cases where slurrification of cuttings will take place with seawater. This already occurs with CRI and could be expected to be of more importance where slurries are moved from one rig to another where inter-field transfer is permissible. Also, cases exist where the disposal option available does not warrant dilution by OBF and seawater will be the economic carrier fluid for the cuttings.

Background Information

The problem of moving slurries with high solids volume fractions is not a new one. The mining and mineral processing industries have been dealing with such slurries for a long time. The main problem related to oilfield slurries is their heterogeneity, which is a function of the rock material being slurried, the retained fluid characteristics (such as OBM) and the diluting fluid characteristics. There are a number of factors which

affect slurry viscosity (figure 1 from [Ref 2]). These include particle size, shape, concentration, mechanical properties of the particles, physico-chemical interaction between particles and liquid (e.g. flocculation, hydrodynamic interaction) and liquid viscosity. Drilling waste slurry particle characteristics will depend on lithology drilled as well as the drilling parameters for the given well profile (bit type, mud type, solids control equipment, WOB, trajectory, etc). With such a list of variables to consider, we envisage that no two slurries will be the same and engineering solutions for slurry handling will have to be tailored on a case by case basis. As well as these factors, there is also the issue of particle comminution due to the grinding effect of the pumps used to circulate the slurry. This process will generate increasingly smaller particles, thereby exposing new surfaces to be wetted by the liquid(s) present. Large increases in slurry viscosity can be expected during this process, which could potentially limit the ability of the pumps and the circulating system to handle such a slurry.

The main control the engineer can exert on these slurries is the particle-particle and particle-liquid interaction. By using treatment chemicals it should be possible to engineer the slurry viscosity to achieve three objectives:

1) Optimise the solids loading of the slurry (i.e. minimise dilution).
2) Optimise the slurry viscosity to enable pumping and slurry transfer.
3) Optimise the slurry stability to minimise settling during transit.

To achieve these objectives we require a technique to enable measurement of the slurry viscosity during the optimisation process. In this study we have adopted two methods for achieving this. One is the standard oilfield coaxial cylinder viscometer and the other is a pipe viscometer.

Pipe viscometers have been employed to measure fluid viscosity for various oilfield fluids, including fracturing fluids, hydrate slurries and cementing fluids. Cement slurries are the closest to waste slurries in terms of the high solids volume fraction in many of them. Bannister [Ref 3] and Mannheimer [Ref 4] observed that flow curves of cement slurries in small diameter pipes are diameter dependent. However, experimental results have also been published showing that the diameter dependency can be neglible for large diamater pipes and above a minimum shear rate or shear stress [Ref 5]. Comparison of rheological measurements made with a coaxial cylinder viscometer and a pipe viscosmeter have been made by several authors. Denis and Guillot [Ref 5] showed that a reasonable agreement between pipe and coaxial cylinder viscometers can be obtained, provided the rheological data is not affected by slippage at the wall. Other studies found significant differences between the two sets of data [Refs 3, 4]. Shah and Sutton [Ref 6] tried to obtain statistical correlation between the measurements performed with a standrard oilfield viscometer and a pipe viscometer. In summary, they found that plastic viscosities obtained with the pipe viscometer were of the order of 10% lower than those obtained with a coaxial cylinder viscometer. For the yield stresses, those obtained with the pipe viscometer were between 0 – 27% higher than those obtained with the coaxial cylinder viscometer.

Viscosity Measurement Test Methods

Coaxial Cylinder Viscometer - A standard oilfield coaxial cylinder viscometer was used to measure the slurry viscosity. The slurry, contained in a cup, is sheared between an outer sleeve (the rotor) and an inner cylinder (the bob), which is attached to a torque measuring device. The configuration of the equipment during these tests was a rotor (R1) with an inner diameter of 18.4 mm and a bob (B3) with an outer diameter of 8.6 mm, thus leaving an annular gap of 9.8 mm. This configuration was used to accommodate large particles in the annular gap. As well as the larger annular gap, the maximum rotational speed of the viscometer was set at 300 rpm and not 600 rpm. This is due to particle exclusion and un-repeatable values for slurries at high rotational speeds. This effect is very similar to that found for cement slurries [Ref 7].

The coaxial cylinder viscometer configuration and procedures adopted for this study meant that the shear rate range covered was 0.8 – 80.4 s^{-1}. Due to the very viscous nature of many of the slurries we were looking at, the dial reading would have been offscale for many of the viscosity meaurements when using the standard oilfield configuration (rotor R1, bob B1).

Pipe Viscometer - A simple pipe viscometer was configured as shown in figure 2 and described in Meeten [Ref 8]. A diaphragm pump connected to a regulated compressed air supply circulated the fluid unidirectionally from the reservoir to the pump, through the pipe and back to the reservoir. For present purposes the volumetric flow rate Q will be taken as constant over the cycle and given by

$$Q=NV_c$$

where N is the number of strokes per second and V_c is the swept volume per diaphragm chamber (80 mL). At any given pressure, the pump rate N is inversely related to the plastic viscosity η of the fluid being pumped, such that $1/N \propto \eta$

Testing showed that the force exerted by elasticity of the diaphragm is always small compared with the force exterted upon it by the air pressure. If the elasticity of the diaphragm is negligible, the pressure of the fluid in the chamber during each stroke is given by the compressed air pressure. The air exhausted by the pump corresponds to the air removed by any diaphragm as it is in suction, i.e. as its chamber is filling. This exhaust flow suffers periodic pressure and flow-rate fluctuations corresponding to the pneumatic switch changeover. These are large enough to actuate a small pressure switch attached to the exhaust which enables the period per chamber, or frequency *N*, to be measured electronically.

The pipe was commercial nylon tubing. Although we evaluated pipes with different lengths and diameters, all the tests reported in this paper were conducted using 3 m pipe length and 12.7 mm diameter. Prior to evaluating slurry properties, repeatability tests were conducted with the pipe viscometer. A refined petroleum oil with a viscosity of 77 cP was repeated 3 times, as was a concentrated polymer solution with a high shear stress. Figure 3 indicates excellent repeatability between the three repeats for both fluid types.

Slurry Viscosity Results – Oil based cuttings + OBF

General – At this stage of the investigation into slurry properties, we wanted to control the variability of the cuttings so we could limit variability in the system and understand some of the processes involved. Therefore, synthetic cuttings were used comprising 4 different materials of different particle size. The range in particle size covered a few microns up to 2 mm. This will allow comparison between tests whereas using real cuttings material would be difficult in terms of controlling their physicochemical properties. The different solids used and their particle sizes are given in table 1. Oily cuttings were generated by combining 15 wt% OBM with the cuttings material and rolling overnight to homogenise. An oil-based slurry was then mixed by combining 50 v/v% cuttings+ mud with a standard OBM (11.6 ppg, 70:30 oil:water ratio).

Coaxial cylinder viscometer – the base slurry viscosity was characterised using the coaxial cylinder viscometer, then incremental additions of various additives were made. The resulting dial readings and notes on the slurry stability were made.

Figure 4 illustrates the resulting rheograms. As can be seen in this shear rate range, the additions of surfactant can have a dramatic effect on the slurry shear stress. In this example, for any given shear rate, the addition of Surfactant A can reduce the slurry shear stress by 80-90%.

The same methods were used to analyse additions of various surfactant chemistries to the oil based slurry. 30 surfactants were tested ranging from 1-10 v/v%. The results of these tests in terms of the effect of the chemical treatment on the base slurry plastic viscosity and yield point are shown in figure 5. It is evident from this plot that the chemical treatment can have a widely different effect on the slurry properties. Further information on the performance of the chemicals can be gleaned from the quadrant representing both a reduction in the PV and YP (figure 5-right). Observations of the slurry stability in the rheometer cup indicate that significant settling of the slurry particles occurred for some of the suspensions, whilst not for others. We could therefore draw a tentative line through the graph, indicating treatments which gave rise to good, relativley low, slurry viscosity whilst maintaining enough yield stress to suspend the cuttings. Conversely, we could also identify treatment chemicals which were very efficient in thinning the slurry, but led to slurry stability problems (i.e. settling).

Pipe Viscometer - Some of the additives which performed the best during the coaxial cylinder viscometer tests were evaluated using the pipe viscometer. The same base slurry detailed above and in table 1 was used. Once the base slurry had been circulated around the system and the pressure/stroke rate data had been noted, then additions of chemical treatments were made to the pipe viscometer reservoir. The slurry was circulated a number of times around the system, then the pressure/stroke rate data noted. Using this method, incremental additions of treatment chemicals could be tested while measuring the slurry pumpability.

Figure 6 shows the effect of the additions on the slurry viscosity, as measured by the pipe viscometer. This illustrates the increased pump stroke rate (i.e. slurry flow rate) for any given pressure drop. Optimisation of the chemical treatment showed that there are benefits to be gained from correct engineering of the slurry treatment. In terms of the benefit of a surfactant treatment to the slurry, figure 7 shows that only 1% addition of Surfactant B to the slurry improved the stroke rate (i.e. flow rate), at 43 psi, by 75%. Figure 8 shows the increased pump rate data, at two different pressure drops, for the pipe viscometer after chemical treatment of the oil-based slurry. The treatment consisted of two chemicals, Surfactant B and Chemical C. For treatment #1 we see the effect of the addition of 5% Surfactant B plus 1% Chemical C. However, for Treatment #2 we have changed the concentration of the products to 5% chemical C and 1% surfactant B. The increase in stroke rate from the base slurry is doubled (i.e. 100% increase). Treatment #3 is the same as #2, except the order of

addition is changed, where the surfactant is added first. The increase in stroke rate is not as dramatic. These results show that the chemistry of the treatment chemicals is important as well as the order of addition.

Slurry Viscosity Results – Oil based cuttings with seawater

General – The same mineral phases were combined, as per table 1, to create synthetic cuttings ranging in size from few microns up to 2 mm. OBM was added to the cuttings (15 wt%) and then rolled overnight to homogenise. 46 v/v% (66 wt%) cuttings+mud were then mixed with 56 v/v% (34 wt%) seawater to generate the sewater-based slurry.

Coaxial cylinder viscometer – the base slurry viscosity was characterised using the coaxial cylinder viscometer, then incremental additions of various additives were made, including wetting agents, dispersants and thinners. The resulting dial readings and notes on slurry stability were made.

Figure 9 illustrates the resulting rheograms. As can be seen, in this shear rate range, the base slurry has a very high viscosity which can be reduced dramatically by additions of only 1% surfactant. Increasing the surfactant dose doesn't significanlty improve the slurry rheology. Figure 10 also shows the reduction in the base slurry PV and YP after additions of 1% surfactant. We can observe that the slurry PV can be dramatically decreased by these additions. It is possible that some settling and particle exclusion from the annular gap is occurring during these tests which would accentuate the PV reductions. The YP can also be significantly reduced, although not to the same degree as the PV. This bodes well in terms of the slurry stability to settling.

Pipe Viscometer – Figure 11 shows the pipe viscometer data for the base slurry in seawater and the effect of the addition of 1 and 5 v/v% Surfactant W. 1 v/v% treatment of Surfactant W dramatically reduced the slurry viscosity. For example, where N=0.6 the pressure drop for the slurry has been reduced by 48%, and where N=2 the pressure drop was reduced by 32%. The effect of various other surfactants were tested on the seawater-based slurries, and all performed very well at low concentrations. It appears from these few tests that the variability in response for the seawater-based slurry treatments is not as variable as the oil-based slurries.

Discussion

Drilling waste slurries will have widely different characteristics and properties due to the heterogeneity of the drilled cuttings and liquid phases present. Mechanical comminution of the particles and chemical instability of the rock in contact with the liquid(s) present will expose new surfaces which will need wetting. Large increases in slurry viscosity can be expected which will potentially limit the pumping and transfer of the slurry. The results reported in this study show that engineering the slurry, in terms of the chemical treatment, can significantly improve the slurry pumpability. This will permit the engineer at the rig-site to treat the slurry to achieve a suitable viscosity for transfer and transport whilst minimising dilution. The results also showed that both the treatment chemistry and order of addition were important to achieving a good fluid viscosity.

For the slurries using seawater as the dilution fluid the addition of small amounts of surfactants were extremely effective in reducing the viscosity. However, significant settling was also observed for these slurries which could have implications for storage and transport. If settling is a problem, then slurry viscosification can be attempted. Some evaluation has been completed of slurry stability during static and dynamic ageing. The latter is important in terms of representing shear of the slurry due to boat movement during transport. This is an area for further work.

The treatment of waste slurries must be approached from an economic viewpoint and whether it is a commercially viable process. The difficulty in arriving at definitive figures for whether a chemical treatment to optimise the slurry dilution is an economic one will depend on local market factors. For example, chemical treatment and minimising slurry dilution where an OBM is the diluting phase could save money. The OBM has a commercial value and any reduction in the dilution volume can have significant cost savings, both in terms of the OBM cost and the reduction of the transport, remediation and disposal costs.

Conclusions

- Drilling waste slurry properties are a function of the of the rock cuttings characteristics, the nature of the retained fluid on the cuttings and the properties of any fluid(s) added to the slurry. With such variability, we envisage that no two slurries will be the same and engineering solutions for slurry handling will be tailored on a case by case basis.
- We approached slurry characterisation by measuring the slurry viscosity using a coaxial cylinder viscometer and a pipe viscometer. The pipe viscometer utilised in this study proved highly effective in characterising slurry pumpability.
- Over 30 surfactants were evaluated in terms of their effect on oil-based slurry viscosity. It was possible to identify additives which proved efficient in terms of thinning the slurry viscosity whilst retaining a suitable shear stress for slurry suspension.
- Results for the analysis of oil-based slurries with the pipe viscometer showed not only was the chemistry

of the additives important, but also their order of addition.

- For the seawater-based slurries, the additives tested were highly efficient in terms of reducing the viscosity, even at low concentrations.
- The pipe viscometer data for the seawater-based slurries illustrated the effectiveness of additions of surfactant. At low pump rates, the effectiveness of the additive was more pronounced, where a 48% reduction in the pressure drop relative to the base slurry was found.
- As well as the engineering of the slurries, the optimisation of the slurry properties must be approached from an economic viewpoint. The benefit of chemical treatment versus the reduction in slurry volume will have to be evaluated on a local basis, where all the different costs (transport, remediation, disposal, treatment chemicals, etc) will have to be considered.

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	SOLIDS PARTICLE SIZES D_{50} (μm)	CONCENTRATION IN CUTTINGS SLURRY (%)
Hymod Prima Clay	7.8	30
Calcium Carbonate 1	119	30
Calcium Carbonate 2	495	20
Sand	974	20

Table 1: Synthetic cuttings were made up of these 4 phases in the concentrations indicated. Note the top-size of the sand was 2000 um.

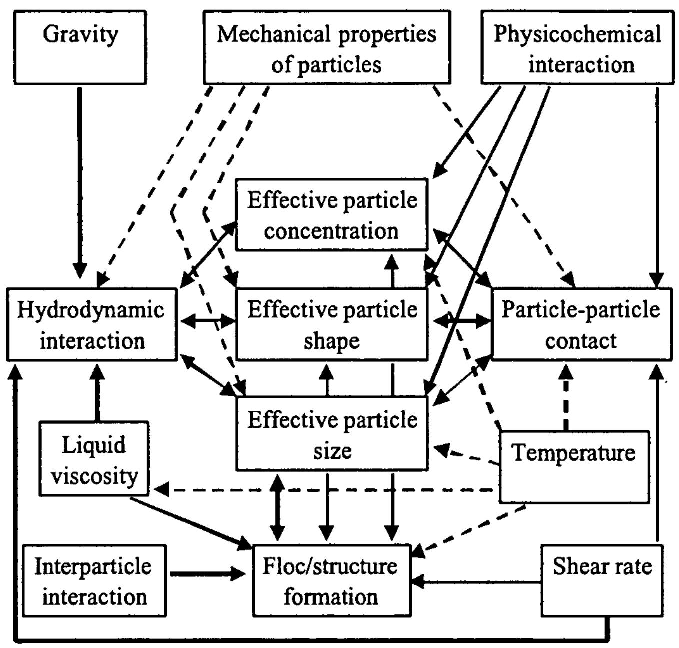

Figure 1: Interaction of factors affecting slurry viscosity [Ref 2].

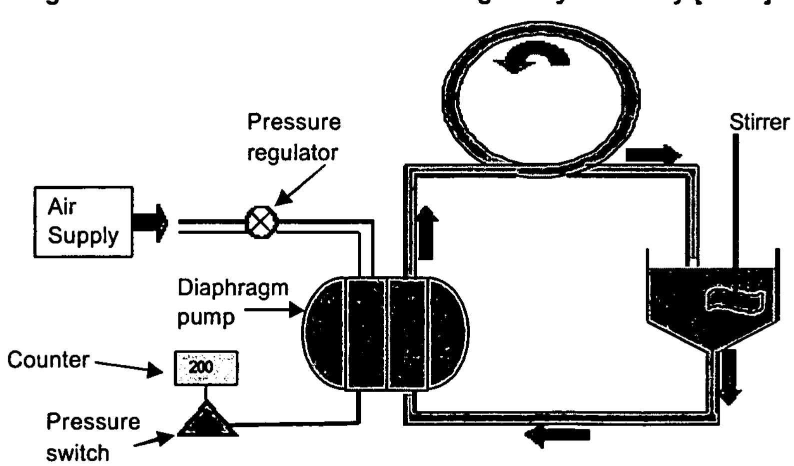

Figure 2: Schematic diagram f th Pip Visc meter.

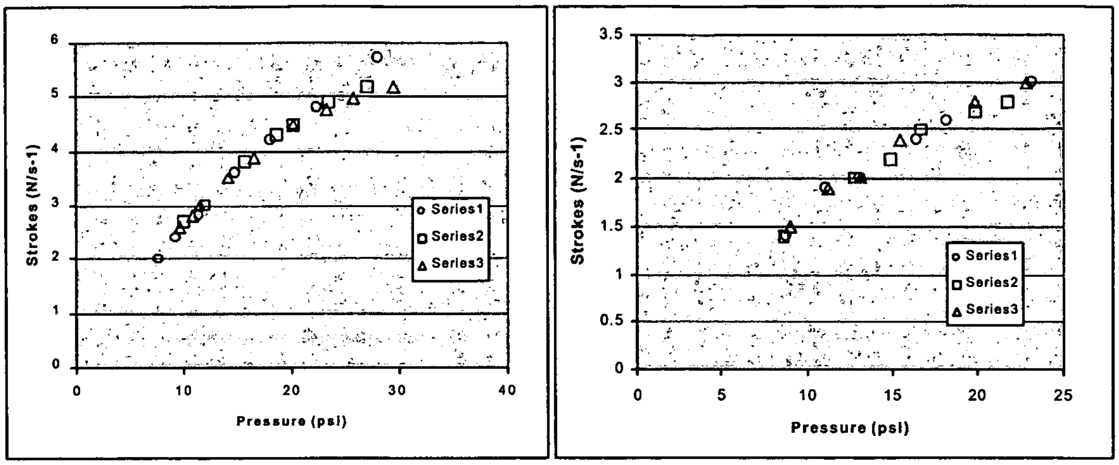

Figure 3: Repeatability tests using the Pipe Viscometer. Data on the left from viscous base oil repeated 3 times; data on the right from concentrated polymer solution repeated 3 times.

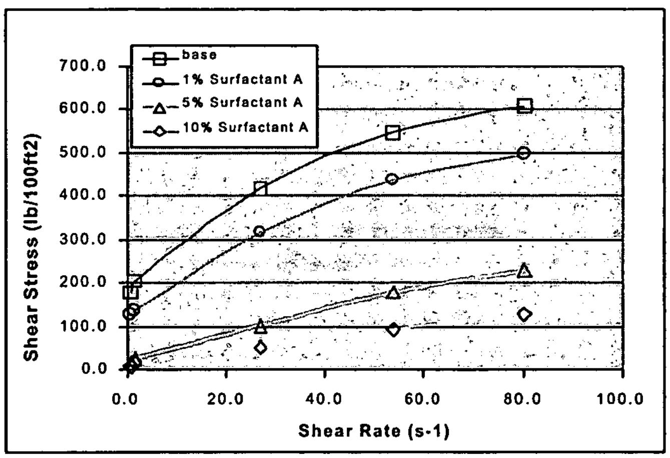

Figure 4: Rheogram for oil-based slurry and effect of additions of Surfactant A.

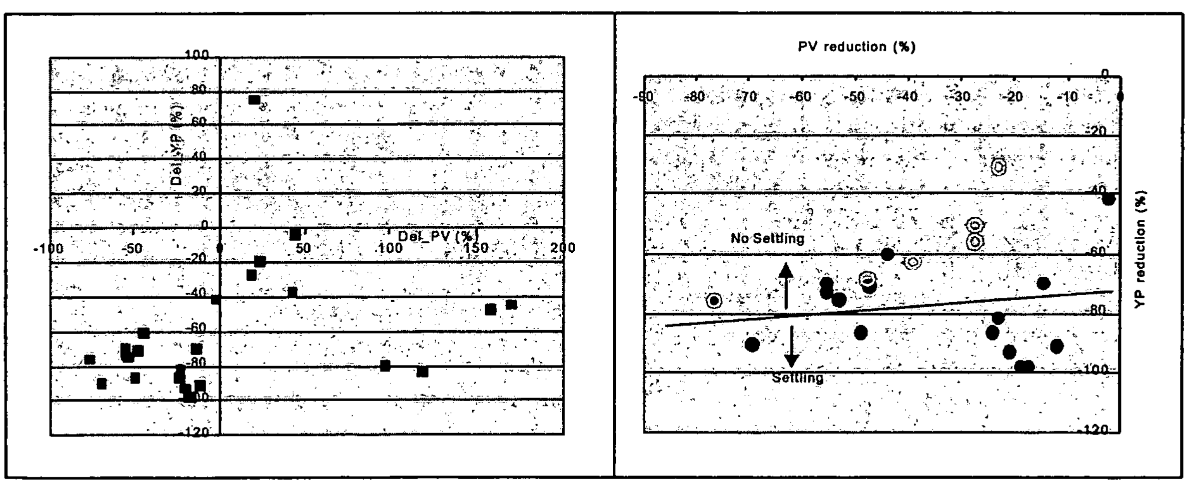

Figure 5: Affect f various surfactants n the il-based slurry rhe logy. Graph n the right represents the bottom-left quadrant f the graph on the left, f cussing where both PV and YP have been reduced.

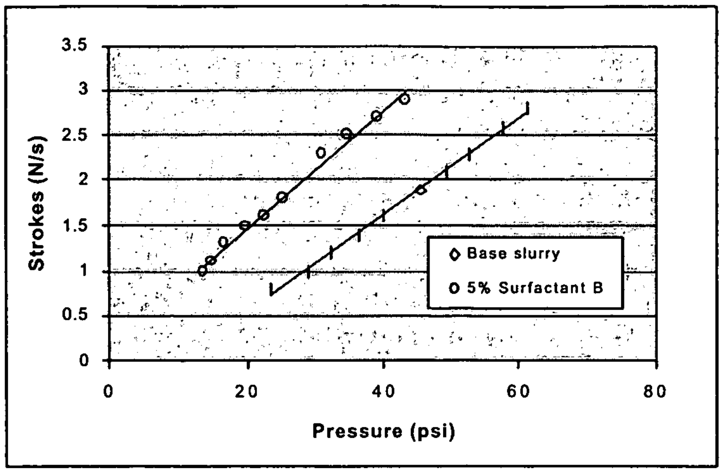

Figure 6: Pipe Viscometer data for the oil-based slurry before and after treatment with surfactant B

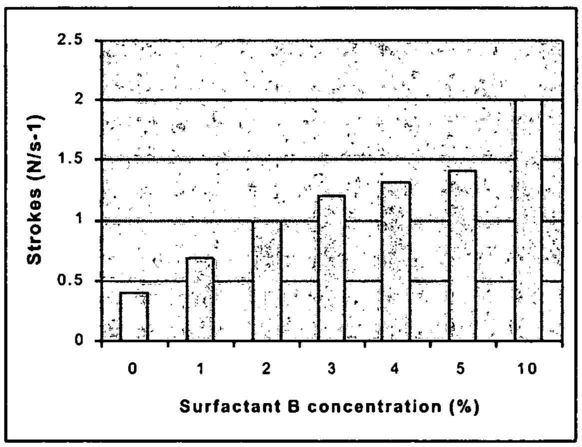

Figure 7: Effect of Surfactant B on the oil-based slurry pump rate (i.e. flow rate) at a constant 43 psi pressure drop.

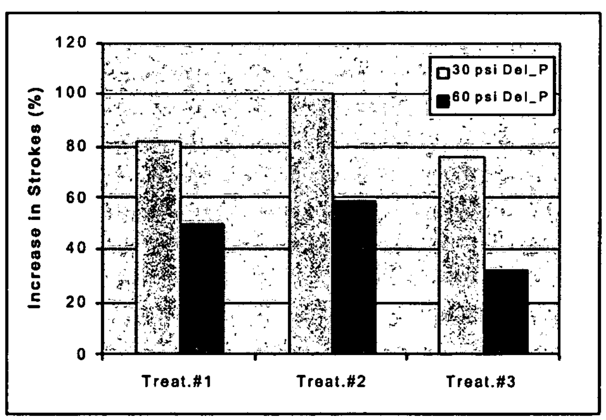

Figure 8: Improvement in stroke rate at different pressure dr ps due t treatment with Surfactant B and Chemical C and change in rder f addition.

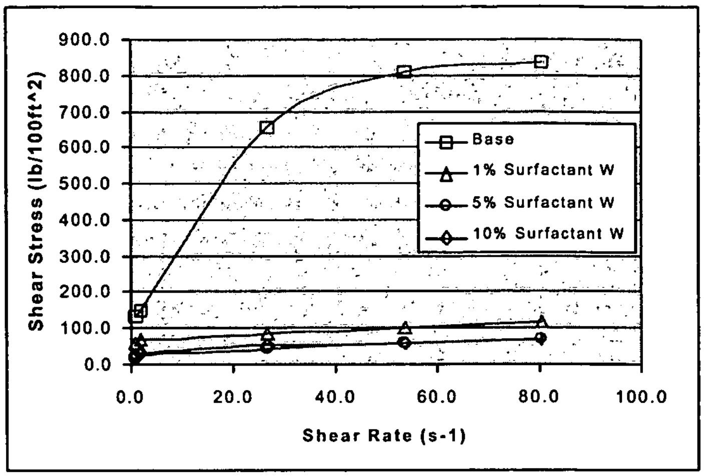

Figure 9: Rheogram for the seawater-based slurry and the effect of additions of Surfactant W.

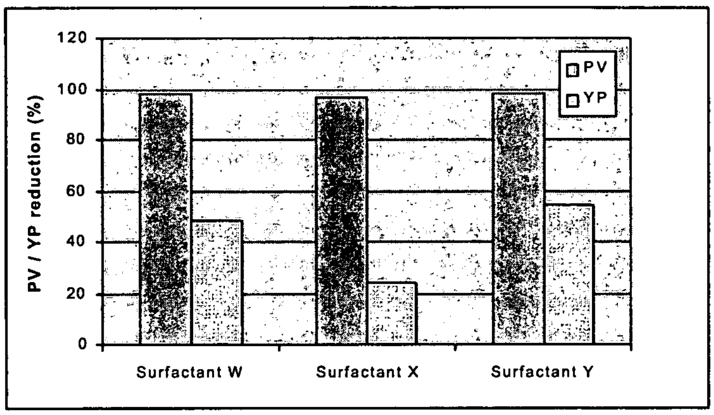

Figure 10: Surfactant additions were extremely effective at reducing the viscosity of the seawater-based slurry.

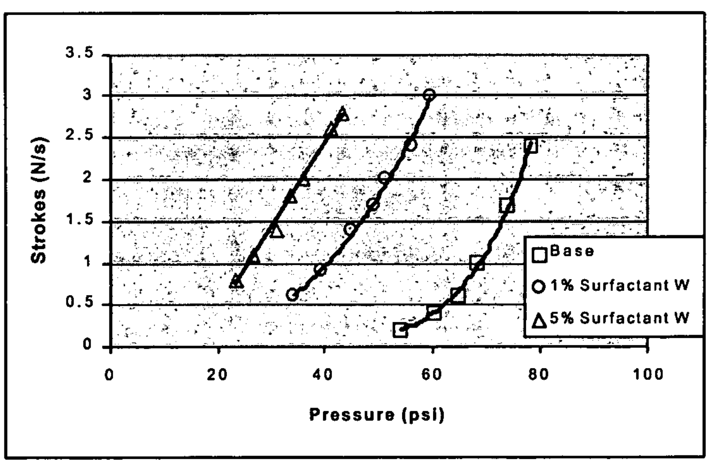

Figure 11: Pipe viscometer data f r the seawater-based slurry and the effect f additions f Surfactant W.